Notice of References Cited	Application/Control No. 10/528,076	Applicant(s)/Patent Under Reexamination TAKANO ET AL.	
	Examiner Meiya Li	Art Unit 2811	Page 1 of 1

U.S. PATENT DOCUMENTS

*		Document Number Country Code-Number-Kind Code	Date MM-YYYY	Name	Classification
*	A	US-5,306,705 A	04-1994	Holcomb et al.	505/191
*	B	US-2002/0025586 A1	02-2002	Takano et al.	438/2
*	C	US-6,682,621 B2	01-2004	Takano et al.	156/89.12
	D	US-			
	E	US-			
	F	US-			
	G	US-			
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FOREIGN PATENT DOCUMENTS

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	N					
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NON-PATENT DOCUMENTS

*		Include as applicable: Author, Title Date, Publisher, Edition or Volume, Pertinent Pages)
	U	K. K. Ng. Complete Guide to Semiconductor Devices. John Wiley & Sons, Inc., New York, 2002. pp. 570-573.
	V	
	W	
	X	

*A copy of this reference is not being furnished with this Office action. (See MPEP § 707.05(a).)
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COMPLETE GUIDE TO SEMICONDUCTOR DEVICES

Second Edition

KWOK K. NG
Agere Systems
Murray Hill, New Jersey

IEEE
IEEE Press

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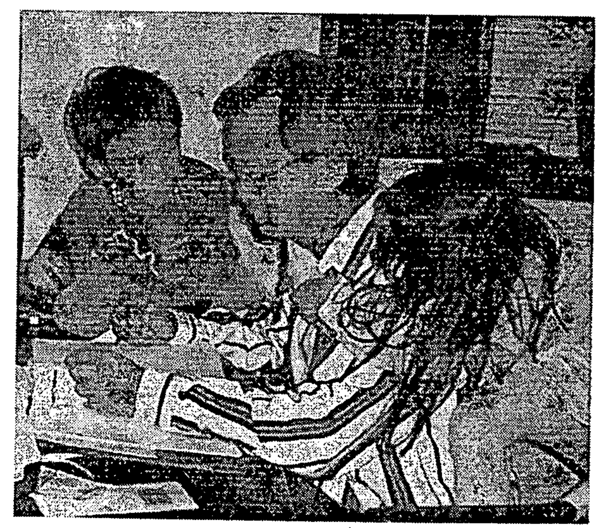
To my family—

Linda,
Vivian, Valerie, and Kyle



"All it takes is concentration"
Author working at home, flanked by son Kyle and daughter Valerie. Picture taken by other daughter Vivian.

where θ is the phase difference and J_c is the critical current density. Equation (A2.3) gives the maximum supercurrent for which the voltage across the Josephson junction V is zero. This is known as the *dc Josephson effect*. A second Josephson equation relates the phase difference to the applied voltage as follows:

$$\frac{d\theta}{dt} = \frac{2qV}{\hbar} \quad . \tag{A2.4}$$

Substitution of Eq. (A2.4) into Eq. (A2.3) gives

$$J = J_c \sin\left[\left(\frac{2qV}{\hbar}\right)t\right] \quad . \tag{A2.5}$$

The current is now a time-varying function and is known as the *ac Josephson effect*. The frequency of oscillation is controlled by the voltage, and is given by

$$f = \frac{2qV}{h} \quad . \tag{A2.6}$$

The dc characteristics of a Josephson junction are shown in Fig. A2.6(a). With $V = 0$, the supercurrent depends on θ and it has a maximum value of J_c. In the range $0 < V < E_g/q$, oscillation occurs but the dc value is near zero. Only a

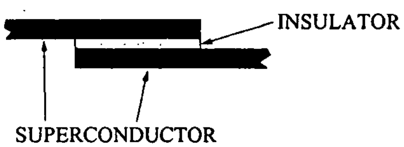


FIGURE A2.5
Schematic structure of a Josephson junction.

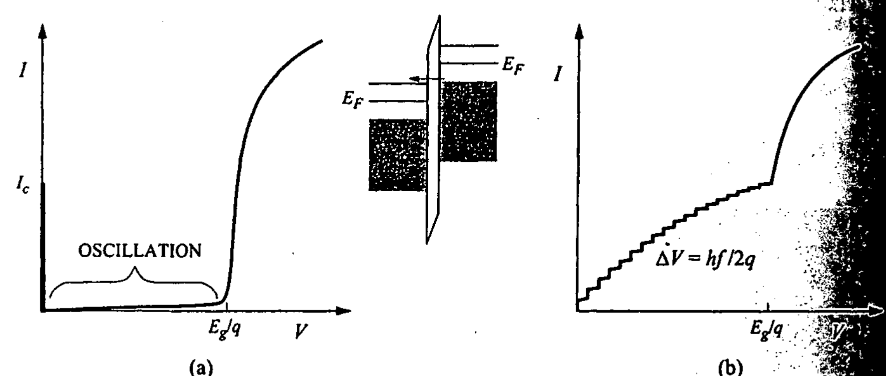


FIGURE A2.6
(a) Dc characteristics of a Josephson junction, and (b) when exposed to microwave radiation. The inset is the energy-band diagram when bias is comparable to the energy gap.

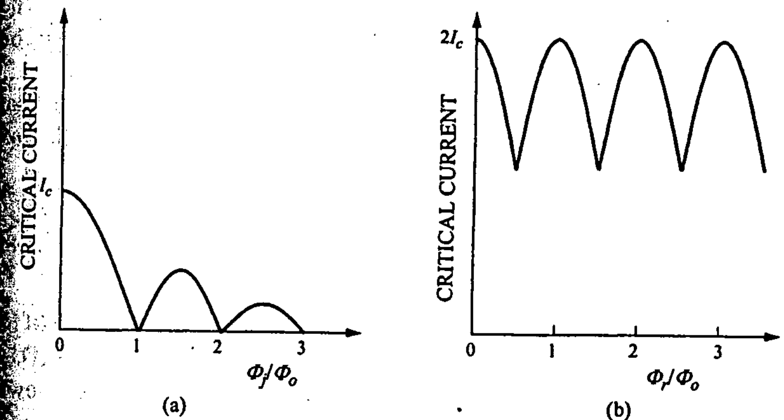


FIGURE A2.7
Critical current as a function of magnetic flux for (a) a Josephson junction and (b) a SQUID. Notice that since $\Phi_r \gg \Phi_j$ for the same magnetic field, the horizontal scales are vastly different.

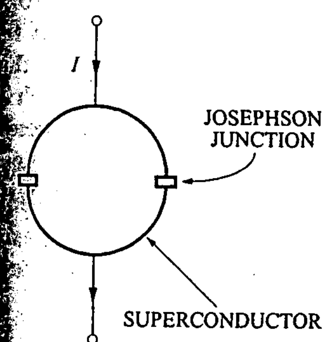


FIGURE A2.8
Schematic circuit diagram of a SQUID.

small dc tunneling current exits. At $V \approx E_g/q$, tunneling current rises rapidly. This condition is depicted by the energy-band diagram in the inset, which shows that energy states are available for tunneling, analogous to a tunnel diode.

The Josephson junction has many applications. The dc switching characteristics of Fig. A2.6(a) can be used to implement logic and memory. The ac Josephson effect can be used not only as a microwave generator, but also as a detector. When exposed to a microwave of frequency f, the characteristics are shown in Fig. A2.6(b). There is a current step whenever

$$V = \frac{N_i hf}{2q} \tag{A2.7}$$

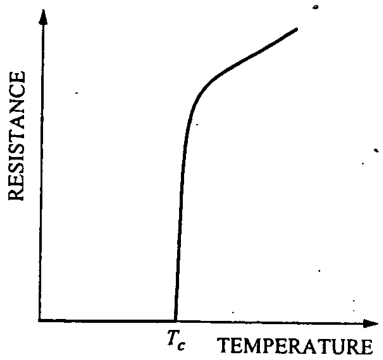


FIGURE A2.1
Resistance-temperature characteristics showing the transition of superconductivity.

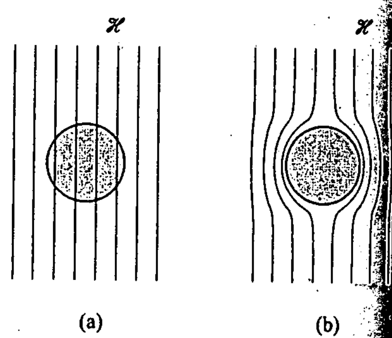


FIGURE A2.2
Magnetic-field pattern surrounding (a) a normal conductor and (b) a superconductor.

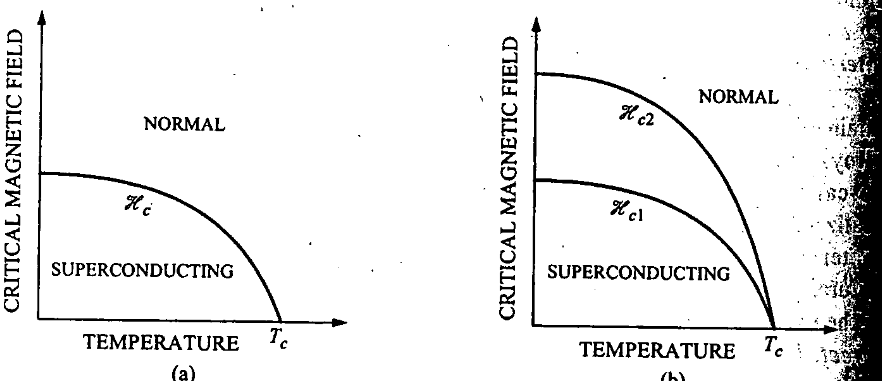


FIGURE A2.3
Critical magnetic field as a function of temperature for (a) a type-I superconductor and (b) a type-II superconductor.

means that the supercurrent cannot exceed a level that produces such a magnetic field value. The supercurrent therefore also has a limit.

Superconductivity is a quantum-mechanical phenomenon, explained in the following by the formation of Cooper pairs, leading to an energy gap. The resistance of a normal conductor is due mainly to phonon scattering and impurity scattering. At a temperature below T_c, electrons rearrange themselves into *Cooper pairs*. The formation mechanism is phonon related. Qualitatively, one electron interacts with the lattice to produce a local deformation (a phonon), and a second electron is attracted to this phonon to form a Cooper pair. The energy of this pair is lower than that of the individual electrons, by an amount called the *energy gap parameter* Δ (Fig. A2.4). The BCS theory also suggests that free electrons have

this energy Δ above the Fermi level. As a result, an energy gap E_g of 2Δ appears. Since any scattering event must involve the exchange of energy, the existence of an energy gap inhibits scattering of the Cooper pairs. This is different from a normal conductor, where an electron can gain any amount of energy. This energy gap has a value of $\approx 4kT_c$ and is on the order of a few meV for a T_c of ≈ 10 K. The existence of such an energy gap has been confirmed by optical absorption spectra.

In a Cooper pair, the two electrons have opposite spins and momenta. Their wavefunctions are also coherent such that they can be treated as one entity. In fact, in the superconducting state, all Cooper pairs and thus the entire superconductor can be described by a single wavefunction. This has an interesting consequence when the superconductor is formed into a ring. The phase difference around the ring must be a multiple of 2π. This leads to flux quantization

$$\Phi_r = \frac{N_i \pi h}{q} \equiv N_i \Phi_o \tag{A2.2}$$

where Φ_r is the total magnetic flux passing through the ring. This phenomenon is utilized in the SQUID.

The potential applications of superconductors are enormous. Having the property of zero energy loss, they will be useful for, to name a few examples, power transmission, electromagnets, and motors. Another area of application is IC interconnects for achieving minimum RC delay. The limitations of superconductors are a required low-temperature environment and a low-current capability.

The *Josephson effect* was named after its inventor, who did this work in 1962 as a student, and he was awarded the Nobel prize in 1973. A Josephson junction simply consists of two conductors sandwiching a thin barrier layer of less than 20 Å, with at least one of the conductors being a superconductor. For the discussion here, both are assumed to be superconductors (Fig. A2.5). Since the barrier is thin, the two superconductors communicate and their wavefunctions overlap to give the following relationship:

$$J = J_c \sin\theta \tag{A2.3}$$

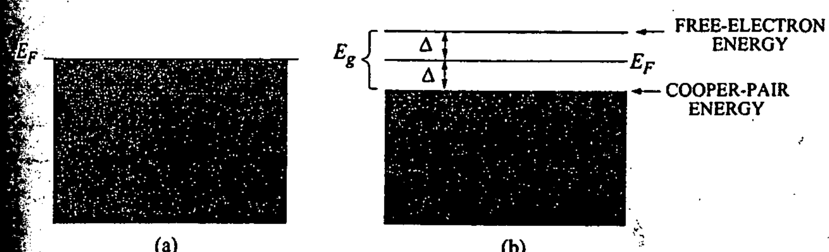


FIGURE A2.4
Energy-band diagrams for (a) a normal metal and (b) a superconductor.